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Analysis of off-grid electricity system at Isle of Eigg (Scotland): Lessons for developing countries

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ABSTRACT

Off-Grid energy systems are growing in popularity as an independent source of energy to satisfy electricity needs of individual households or smaller communities, mainly in developing countries where the main grid is either not developed or the grid is uneconomical to extend due to remoteness of the location. The Isle of Eigg in Scotland has been successfully using a hybrid off-grid system for several years to provide a reliable 24-h electricity supply to the islanders. This ex-post analysis of the Isle of Eigg system investigates its performance and explores possible alternative configurations which could work more effectively and efficiently. Simulations were carried out using HOMER software for the existing system and for alternative configurations of energy generation. It is found that the existing overcapacity has been instrumental in ensuring a reliable supply but continued reliance on diesel generators adds to the cost. More wind power capacity addition can reduce reliance on fossil fuels and modular sizing of generators instead of adding large capacities could have reduced the idle capacity. This experience suggests that providing reliable off-grid electricity supply is possible but is costly without suitable capital subsidies. Appropriate system design suited to the local condition is important for developing a viable system.

1. Introduction

Harnessing of electric power has brought dramatic changes in the way a society functions, particularly in the developed world, to the extent that without electricity the contemporary society would not be able to exist. However, still almost 1.3 billion people (or 18% of the global population in 2011) are living without access to electricity [1] mostly in Sub-Saharan Africa and South Asia. Vast majority of those people live in remote areas where it is either impossible or uneconomical to connect them to the national grid. While off-grid options such as solar home systems (SHS) have emerged in such cases through the support of international organisations and donor agencies, their reach has been relatively limited due to high cost, limited application and poor performance of some of the technologies as well as the image of “inferior or temporary” nature of such options [14]. Moreover, decentralised off-grid systems tend to offer limited electricity supply just to meet the basic needs of lighting and mobile charging and most often the service is available for a limited period of time, say 4–6 h per day. The reliability of supply is also an issue given that they are based on one source of renewable energy such as solar or hydro power, and any fault with the system affects supply reliability.

Against this backdrop of limited, basic-level of supply, a remote island community in Scotland however has been successfully providing reliable, 24-h electricity service to the users through a hybrid off-grid electricity system. The residents are enjoying a modern life-style through use of a diverse array of electrical appliances and are able to meet their electricity needs through this system. This example demonstrates that it is possible to build a mini-grid based on renewable energies to provide electricity for 24 h/day, reliably.

Despite its success, Isle of Eigg has received limited academic attention in terms of reference in peer-reviewed journal papers. Yadoo et al. [16] present a comparative picture between Isle of Eigg and a Nepali off-grid system but the focus of their study was on reverse learning from developing countries about the institutional arrangements and delivery mechanisms. The purpose of this paper is to explain how the Isle of Eigg has achieved its reliable electricity supply to support a modern life style of the islanders and to investigate whether there is any scope for further improvement in its system design. In addition, we explore whether the Isle of Eigg

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model offers any lessons for the developing world, where countries are trying to enhance access to electricity. Although the institutional and economic backgrounds of developing countries are different from what is found in this island, and despite the fact that it is outside the scope of this paper to undertake an in-depth background matching exercise for specific country conditions, this case study may offer some specific factors that are relevant for other projects as well. We try to identify such factors or conditions without necessarily undertaking a detailed socio-economic or regulatory analysis of specific projects or conditions.

The study follows a mixed-bag approach.

a) First, a thorough review of available literature was undertaken for various purposes: 1) to meet the information requirement of the case study; 2) to develop supporting arguments for triangulation and cross-verification; 3) to identify the knowledge gaps; and 4) to identify methodological approaches. The literature was collected through a systematic search of keywords using online search engines, journal databases and other sources including books and reports.
b) Second, specific information on the electricity system at Isle of Eigg was collected from the Eigg Electric Ltd. through personal communication and in-person discussion with the staff during a site visit in the summer of 2014.
c) Third, HOMER, (Hybrid Optimisation Model for Electric Renewables), developed by NREL (National Renewable Energy Laboratory, USA) software was used to carry out simulation exercises considering the present system configuration and alternative system configurations. The purpose of this exercise is to perform an ex-post analysis to verify whether the existing system has been appropriately designed and whether there is any scope for improvement. The simulation results were considered to suggest system improvements and to develop lessons for developing countries.

The paper is organised as follows: Section 2 presents the Isle of Eigg system. Section 3 presents the relevant literature on HOMER-based studies. Section 4 presents the data used in simulation, Section 5 presents the simulation outcomes while the final section discusses the relevance for the developing world and some concluding remarks are presented at the end.

2. Isle of Eigg off-grid electricity system

Isle of Eigg is the second largest island of the Small Isles Archipelago in the Scottish Inner Hebrides. It is located at 56.9° North latitude and 6.1° West longitude. It lies about 20 km (12 miles) off Scottish west coast, south of the Isle of Skye. The island is 9 km (5.6miles) long from north to south and 5 km (3.1 miles) long from east to west. It has 83 inhabitants within 38 households and 5 commercial properties. It is reached by ferry from Mallaig (Fig. 1)..

Its remoteness from the Scottish mainland has proven to be uneconomical to connect to the national grid. Before the electrification project came to life in 2008 the island did not have electricity supply. Most residents used individual diesel generators but a few relied on a small hydroelectricity plant. Batteries/inverters were commonly used to ensure electricity access. The cost to users varied depending on the size of generators used, their running time and cost of fuel but on average most users used to spend £500 per year of diesel generator running cost in2003[1] [2].

[1] Diesel price in 2003 was £0.779 per litre which has risen to £1.35 in 2014. Using the 2014 diesel price, residents would spend about £870 per year on diesel.

Fig. 1. Map of Isle of Eigg (http://www.isleofeigg.net).

The cost of connecting the island to the main grid system in the mainland was estimated between £2 million [2] and £4-5 million [3] but funding for the investment was hard to find and the plan was abandoned. In 2004, it was decided to develop a hybrid electrification system on the site and it took almost four years to put the system in place [see Fig. 2 for the project timeline]. On the 1st of February 2008 the island started to produce its own electricity through a unique system comprising of renewable sources of energy backed up by diesel generators. The electricity is distributed around the island through an underground micro-grid system that supplies energy for 24 h a day.

The off-grid system is made of the following: 119 kW of hydro power capacity using three turbines of 100 kW, 10 kW and 9 kW at three sites, 24 kW of wind power capacity (4 × 6 kW), about 54 kW of solar PV capacity and 160 kW of diesel generator capacity as back-up (2 × 80 kW). The total system installed capacity is about 357 kW. The system specification is presented in Table 1. Fig. 3 provides a few photographs from the site.

The battery bank and the inverter system are at the heart of the system. A 48 V battery with 4400 Ah capacity [4] provides enough storage from renewable energy sources for delivery when the demand arises. The inverters control the frequency and voltage of the grid balancing the demand and supply and controlling power input and output to and from the batteries.

The system load is distributed between 38 households and 5 commercial properties, connected through an 11 km long underground high voltage distribution system. To prevent overloading, household electricity use is capped at 5 kW and that for commercial properties is capped at 10 kW each. This gives the simultaneous total maximum load of 225 kW, but the system demand remains much lower due to load diversity and demand management practices. Each resident was given an OWL energy monitor system which is used by the residents to stay within their load limits. In case the system is overloaded and a back-up system has to be brought in, a provision for penalty exists but this has rarely been used.

The Eigg Electric Ltd., a subsidiary of the Isle of Eigg Heritage Trust, manages the electricity supply and distribution activity on the island. The company has its own board of directors, with at least one of the directors is also a director of the Trust. The company board is responsible for day-to-day management of the company activities but any major decisions with significant strategic and financial implications are referred to board of the Isle of Eigg Heritage Trust. Simple day-to-day maintenance is carried out by local

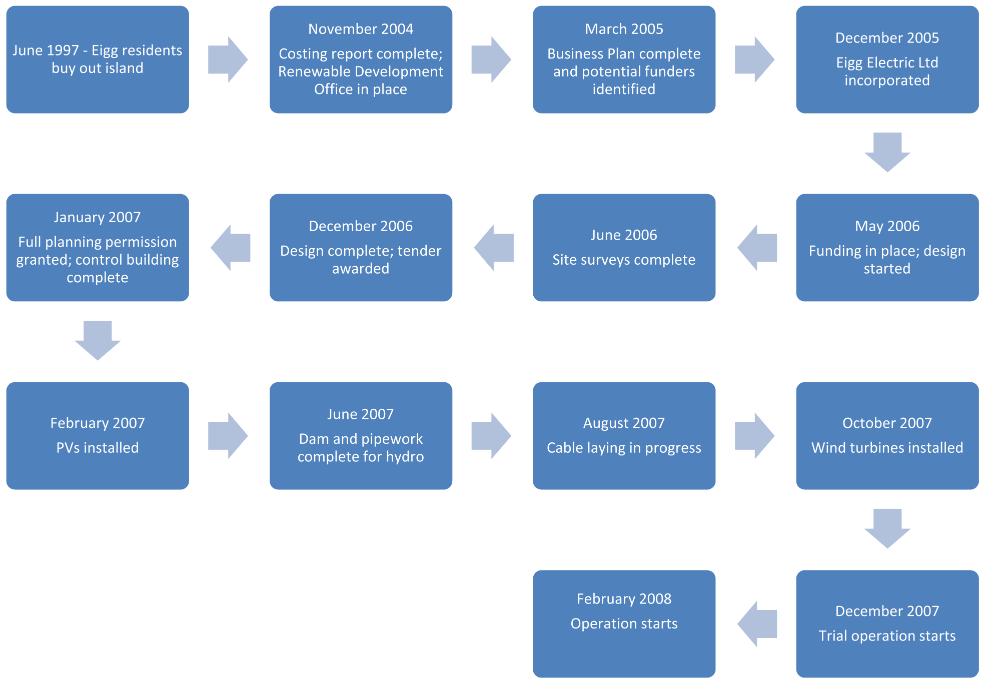

Fig. 2. Isle of Eigg project implementation timeline [15].

residents but professional maintenance work is done by Scottish Hydro Constructing.

The project cost was £1.66 million in 2008 [3]. Funding the investment was a significant challenge for the Isle and was secured from a number of sources as grant as indicated in Table 2. Each consumer pays a uniform rate of £0.2 per kWh. In addition, there is a standing charge of £0.12 for a 5 kW load and £0.15 for a 10 kW load. Consumers also paid an initial connection charge of £500 for a 5 kW load and £1000 for a 10 kW load [5].

The electricity company generates revenue through electricity charges, feed-in tariff and the income from Renewable Obligation Certificates. The solar PV, wind turbines and the micro hydro system qualify for feed-in tariffs while the large hydro is covered by the Renewable Obligation Certificate [ROC] scheme [4]. Although the project has received grant funding, it also benefits from feed-in tariff and ROC payments as the project came into operation prior to the rule change in the United Kingdom that disallows state aids in the form of feed-in tariff or ROC for grant-funded renewable energy projects.

The electricity tariff is designed to provide sufficient funds for system operation and maintenance as well as for component replacement. The tariff in the island is higher than the tariff charged for electricity on the mainland.

Table 1
Specification of system components.

PV array	Power	9.9 kWp
	Modules	60xBP Solar BP3165S PV
	Inverters	(2× SMA Sunny Boy SB-3000)
		21 kWp
		126 × BP Solar BP4180 180Wp PV
		(3 × SMC-7000HV)
		22.5 kWp
		90× REC Solar REC 250 PE 250Wp PV
		(3× SMC-7000HV)
Wind turbines	Model	KW6 Kingspan
	Power	4 × 6 kW
	Inverter	6× SMA Windy Boy WB-6000A
Hydro turbine	Model	Glikes Single Jet Turbo
	Power	100 kW, 9 kW, 10 kW
Diesel generator	Power	2× 80 kW Thistle Generator P80P1
Battery bank	Model	Rolls Surrette 4KS25 PS
	Quantity	4 clusters 24 batteries each
	Inverter	12× Sunny Island SI-5048 5 kW

Source: [11].

3. Literature review

For the purpose of literature review, we do not concentrate on Isle of Eigg alone but consider similar examples of application of renewable energy-based micro grids from around the world. These studies provide support to renewable energy-based off-grid electrification in remote islands and capture the diversity of cases considered in the literature. We also present a brief review of HOMER-based studies. Accordingly, this section is divided into two sub-sections.

3.1. Review of literature on renewable energies in remote areas

A report by IEA-RETD [4] presents a detailed analysis of renewable energy use in remote areas of member countries involved in the Renewable Energy Technology Deployment initiative and showcases a number of case studies, including the Isle of Eigg case. The report has established six different categories of remote areas and focused on different categories of energy requirements for heating and cooling, transportation and electricity. It considered alternative pathways for achieving 100% renewable energy-based services and the financing challenge faced by projects in remote locations. The study concludes that better stakeholder involvement and co-operation is vital for the success of such project initiatives. It also suggests that solutions tailored to local context make projects sustainable but appropriate institutional and political environment to promote renewable energies cannot be ignored either.

Fig. 3. Components of the system from top left: PV arrays, wind turbines, battery bank, diesel generator, inverters system, 6 kW hydro turbine.
Photo credit: Zbigniew Chmiel.

A report by the Friends of the Earth Scotland [15] presents a number of examples of community energy initiatives in Scotland that are helping in harnessing renewable energies at the local level. Although the report goes beyond electricity and is not necessarily targeted toward remote areas, it captures the off-grid electricity cases of Isle of Eigg and Scoraig (where a wind-based off-grid system supplies electricity to households and a school). The report finds that although the community projects are growing in Scotland, they face a number of challenges particularly in the form of uneven playing fields, lack of integration of energy issues in local planning and policies, and equitable access to grid.

While the above reports considered real-life projects, many other studies evaluated the techno-economic feasibility of renewable-based energy supply projects in remote areas. For example, Neves et al. [17] present a review of hybrid renewable energy systems for micro communities in islands and remote villages. They find that data reporting is particularly weak for many such projects and recommend a structured framework for ease of analysis and evaluation. Chakrabarti and Chakrabarty [18] analysed the case of solar PV for an island use in Sagar Dweep, India. The study considered PV and grid extensions as alternative systems and evaluated the options from economic and environmental perspectives. The study shows that grid extension over long distances is not cost-effective. Singhal and Singh [19] present a case study of Neil Island in Andaman island (India) wherein they suggest a renewable-energy based alternative to diesel generators for electricity supply. However, they only consider power supply for 6 h in the evening and the study evaluates the feasibility of an alternative, without reporting a real-life diesel-generation replacement case. Kaldellis et al. [20] present a cost-benefit analysis of renewable energy – energy storage solution for Greek islands and offer an integrated methodology to determine the optimum configuration for island electrification. They consider reliable 24 h supply in one scenario and show that the cost of supply is lower than the marginal cost of electricity generation from the fossil-fuel based system used at present. However, this is only a feasibility study and does not report any real-life case study.

Table 2
Source of project funding.

Source	Amount (£)	Share (%)
European Regional Development Fund	764,000	46%
Scottish Community and Householder Renewables Initiative	196,127	12%
Highlands and Islands Enterprise, Lochaber	313,000	18.9%
Big Lottery Fund	250,000	15%
Island Trust and residents	92,761	6%
Energy Savings Trust	33,940	2%
Highland Council	15,000	0.1%
Total	1,664,828	100%

Source: [3].

3.2. A brief review of HOMER-related literature

HOMER appears repeatedly in the literature as a preferred tool. It can handle a large set of technologies (e.g. PV, wind, hydro, fuel cells, and boilers), loads (AC/DC, thermal and hydrogen), and can perform hourly simulations. It is an optimization tool that is used to decide the system configuration for decentralized systems through simulation using different system configurations when necessary input data is supplied. It creates a list of feasible system designs and sorts the list by cost effectiveness that helps to make a decision about the optimal system configuration. In addition, it comes with a large database of technologies that facilitates the component selection process.

In the following paragraphs, a brief review of selected literature on HOMER application is presented. Givler and Lilienthal [21] conducted a case study of Sri Lanka where they identified when a PV/diesel hybrid becomes cost effective compared to a stand-alone small solar home systems (50 W PV with battery). This study considers an individual household base load of 5 W with a peak of 40 W, leading to a daily load average of 305Wh. Through a large number of simulations, the study found that the PV-diesel hybrid becomes cost effective as the demand increases. However, this study focuses on the basic needs as such and does not include productive use of energy. A study by Kanase-Patil et al. [6] investigated the options to satisfy cooking and electrical energy needs of seven villages in the Almora district of Uttarakhand state in India. The villages are located in hilly and remote locations in a dense forest and 267 households live there. The study considered renewable resources such as biomass, solar power, hydro power and wind energy. The following maximum resource potentials were evaluated for the site: hydro power 293 MWh/year, biomass including crop residues and forest foliage around 190 MWh/year, solar energy 1837 kWh/m^2/year, and wind potential at around 1270 kWh/m^2/year. Out of 28 proposed micro hydro generating options, only 5 would remain functional throughout the year while the rest would be seasonal. A 40 kW rating biomass gasifier was considered to produce energy for 6–8 h a day throughout the year. Potential for biogas is assumed to be at 34 MWh/year. Out of 4 different scenarios utilizing different combinations of renewables one best scenario utilizing hydropower, biomass, biogass, energy plantation, wind and solar was selected as the most feasible for those remote villages. The study also compares the cost of electricity supply using HOMER and LINGO software.

Sen and Bhattacharyya [7] emphasise on the importance of providing reliable and cost-effective electricity to about 1.3 billion people who live without it. They argue that in many cases extension of the main grid is not possible so off grid energy systems are helpful options. They also mention that it is important to use multiple technologies rather than focussing on one or two renewable systems to provide adequate supply to the customers. A hybrid system design can overcome the problem of intermittency of renewable energies and increase reliability of supply. In their research for electrification of remote villages they carry out a case study of an Indian village using HOMER software and find that hybrid systems are technically feasible and economically viable in many locations.

Ranaboldo et al. [8] discuss cost minimization of electricity in micro grid systems through a comparison of costs with stand-alone independent generators. In scattered communities a combination of independent generators into a micro grid, where more powerful generators are installed in places with better resources, brings a cheaper design solution and lower end user prices. They also say that micro-grids for remote areas are the most promising design solutions. The higher utilization of micro-grids will probably lead to lower installation costs and increase in supply quality as it will teach to overcome many technical barriers which are currently faced in such designs.

Kusakana and Vermaak [9] emphasize on the importance of optimal sizing and selection of the components of an isolated hybrid system. According to the authors, many existing schemes often rely on conventional approaches such as “Rule of thumbs” and the “paper based methods” which have their limitations as they rather provide broad guidelines with significant room for improvement. Systems that do not utilize the resources in the best possible way increase cost and reduce the performance.

Dorji et al. [10] analysed the possible options for electrification of a few of remote settlements in the Kingdom of Bhutan, a small neighbouring country of India. A harsh mountainous terrain with not many settlements scattered all over it makes a grid connection impossible in most of the cases. The study considered aspects such as energy needs of households, resources available and current policies and programs on rural electrification. The tool used for analysis was HOMER energy software. The study found that renewable technologies such as wind-battery or PV-battery can be considered as alternatives to grid connections. Also the study revealed that the most economical approach differs from site to site and a careful analysis and modelling of proposed system is necessary in order to make the best design.

Numerous other studies have been reported analysing renewable energy based electricity generation using HOMER. For example, Himri et al. [22] present a study of an Algerian village; Nandi and Ghosh [23] discuss the case of a Bangladeshi village, while Nfah et al. [24] and Bekele and Palm [25] provide case studies of Cameroon and Ethiopia respectively.

However, most of these studies are hypothetical in nature, rely on representative households consuming identical levels of energy for a given period of time, use generic technology/financial information and thus provide an overall understanding of the hybrid option. There is no study using Isle of Eigg except those mentioned above [2–5,15,16] and there is no ex-post analysis that has verified the system design issue and identified lessons for developing countries. This paper tries to bridge this knowledge gap.

4. Simulation of the Isle of Eigg system using HOMER

The purpose of the simulation exercise is to investigate whether the existing system has been appropriately designed to produce electricity at least cost given the load and available energy resources at the site. We also investigate whether the configuration can be improved to deliver electricity more effectively.

4.1. System configuration

Fig. 4 presents the system configuration in HOMER. The hydropower and the diesel generator are connected to the AC-side of the bus while the PV and wind generators are connected to the DC-bus. A converter is used to convert AC power to DC and the battery bank stores the energy generated to meet the demand as it arises.

4.2. Load assessment

Fig. 5 presents the monthly electricity production from the system between November 2008 and July 2012. Information on daily or hourly demand could not be availed from the Electricity Company or the Trust owning the company. However, the monthly demand trend shows a summer trough and a winter peak of demand. Accordingly, two different load patterns were considered in the simulation. The average power consumption was calculated by summing up consumption in all months and dividing it by the total number of hours. For winter months the average power consumption equals to 43 kW, while for the rest of the year, the demand came to 35 kW. The average load was distributed throughout the day with different amount of power used depending on time in the day, using the following loading pattern:

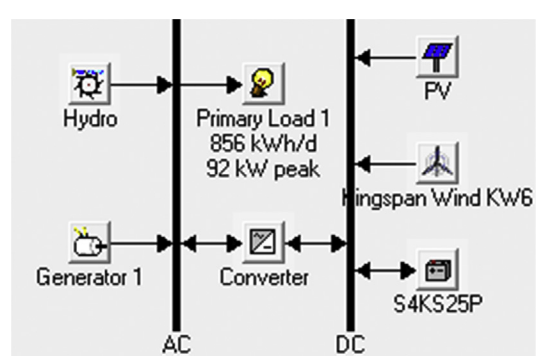

Fig. 4. System configuration diagram in HOMER.

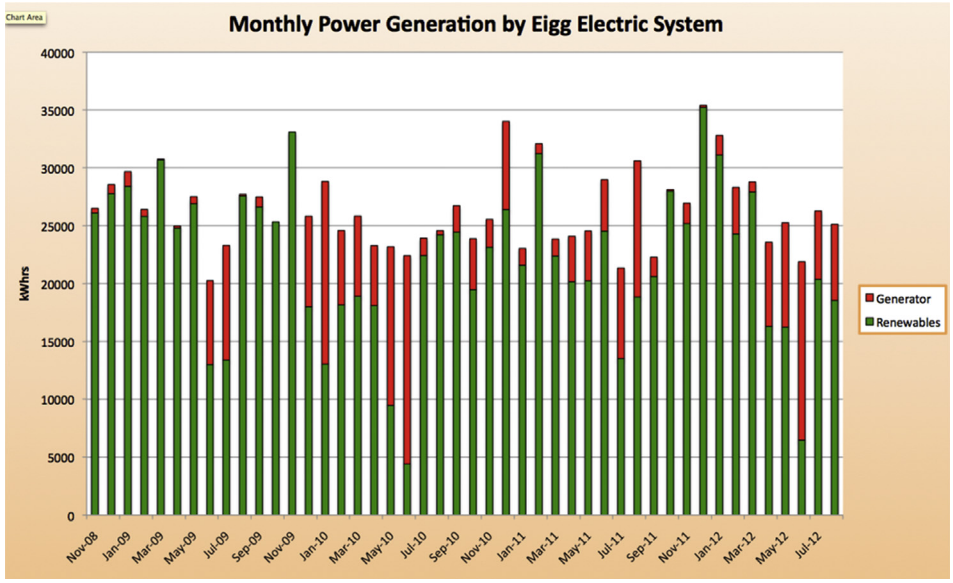

Fig. 5. Electricity consumption/production between Nov 2008 and Jul 2012 [11].

- From between 00:00am to 06:00am the average power minus 20%
- From between 00:06am to 05:00pm the average power minus 5%
- From between 05:00pm to 10:00pm the average power plus 20%
- From between 10:00pm to 00:00am the average power plus 5%

The resultant loads were entered in HOMER and Fig. 6 captures the screenshot of primary load data. The average daily system demand is 856 kWh, with a peak load of 92 kW. It is interesting to note here that although the islanders have a capped load of 5 kW, on average they consume just 20% of the maximum allowable total load. This indicates significant load diversity in the system that allows the system to be run with the installed capacity. The use of energy monitors by the residents helps manage the demand effectively. An alternative scenario of 1000 kWh/day is also used as a sensitivity analysis case.

4.3. Resource assessment and technology features

As indicated earlier, the site offers potential for hydro power, wind energy and solar energy. These resources are presented below.

4.3.1. Hydropower

The site has 3 hydropower units with a total capacity of 119 kW. As HOMER allows only one unit of hydropower, the flow and head characteristics have been adjusted to arrive at the overall power output from the hydro system. The hydro resources are shown in Fig. 6. The head is taken as 124 m and the design flow is taken as 130 L per second. For the simulation of the existing system, no capital cost is used as the funding came from grants. Replacement cost is taken as £120, 000 and the life time of the plant is taken as 30 years although it is very likely to last much longer. The turbine efficiency is taken as 75%.

4.3.2. Solar PV

HOMER sourced solar irradiation data for the site from NASA website (see Fig. 7). The average scaled annual solar radiation equals to 2.79 kWh/m^2/day. HOMER also calculates clearness index which is the amount of global solar radiation on the surface of the earth divided by the extra-terrestrial radiation at the top of the atmosphere.

Photo voltaic panels were installed in three arrays. The first one was installed in 2008 when the project started; two others were subsequently added in 2011 and 2013. The total installed PV capacity at the site is 53.4 kWp. Because HOMER does not have an option for adding panels in different time periods, it is assumed that all panels were installed at the same time and the total cost of replacement is based on current prices. The panel life is taken as 25 years and a de-rating factor of 85% is used as specified in panel seller's website [11]. Slope of the arrays has to be at the same angle as the latitude of the island in order to capture the most of sun energy unless the panels are equipped

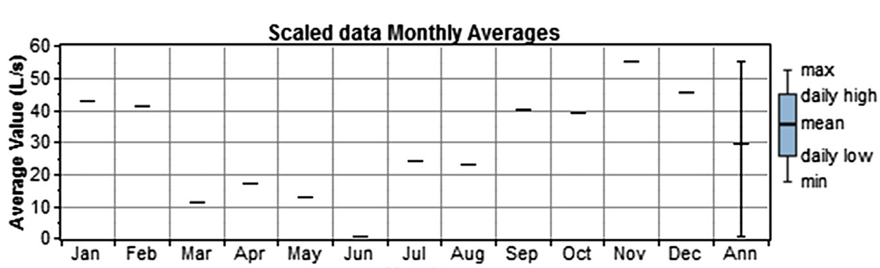

Fig. 6. Hydro resource at Isle of Eigg.

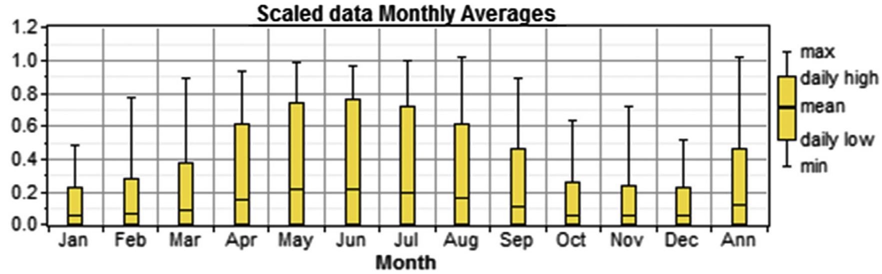

Fig. 7. Solar irradiation at Isle of Eigg.

with tracking system. The azimuth is set as longitude of the island.

4.3.3. Wind energy

A report prepared for the Island Heritage Trust in 2003 [2] shows that the island is a good place for installing wind turbines with good wind speed. Although the report provides the average wind speed at different sites on the island, it did not provide the monthly distribution of wind speed. As there was no recent meteorological data available for wind speed at Isle of Eigg that could be used for simulation in HOMER, we use data from island Tiree lying 50 km south-west of Isle of Eigg [12] as a proxy. The monthly wind data used is shown in Fig. 8.

HOMER has its own database for the most popular wind turbine models but the turbine used on the island Kingspawn KW6 is not included in this database. In order to add this turbine to the HOMER database, its power curve (power output vs wind speed) had to be calculated by using ratio of similar wind turbine. The turbine used to calculate the power curve was available in HOMER database BWC Excel-R 7.5 kW.

It is interesting to note that solar energy complements wind and hydropower quite well at this site – solar radiation peaks during the summer months when wind and water availability for hydropower reduces.

4.3.4. Diesel generator

Diesel generators come on when batteries discharge below 50% of capacity. The site has 2 units of 80 kW diesel generators. The generators have a life of 15,000 h and minimum load ratio of 30%. Two generators were considered separately in the simulation. The diesel price was set at £1.34/l [13]. No limit of consumption has been set up.

4.3.5. Battery banks

4 KS25P batteries have been selected from HOMER database although the model used in the project is 4KS25 PS. There is no difference between the two with regards to capacity, life time or operating conditions. 4 strings of 24 batteries per string were considered as is found on the site.

The replacement cost of battery is taken as £85000 which is slightly lower than current price (£98,000). Battery prices are likely to fall in the future. This is taken into consideration in the above replacement cost. The depth of discharge for batteries is taken as 50% and cycle charging mode is used.

4.3.6. Converters

The basic size of the converter is 5 kW and various sizes up to 139 kW (total existing capacity) were input for the simulation. We have also used a life time of 15 years for converters, an efficiency of inverters of 90%, and that of rectifiers at 85%. The average price of converters is calculated from the converter costs obtained from the site.

4.3.7. Additional inputs

For our simulation, no capacity shortage is allowed and no minimum renewable fraction has been specified. An operating reserve of 10% of hourly load or 10% of solar or wind power output has been maintained. The project life time is set for 25 years and a fixed operation and maintenance cost of £30,000/year has been included to take care of a full-time staff-related cost involved in the maintenance and system operation. Where initial costs are

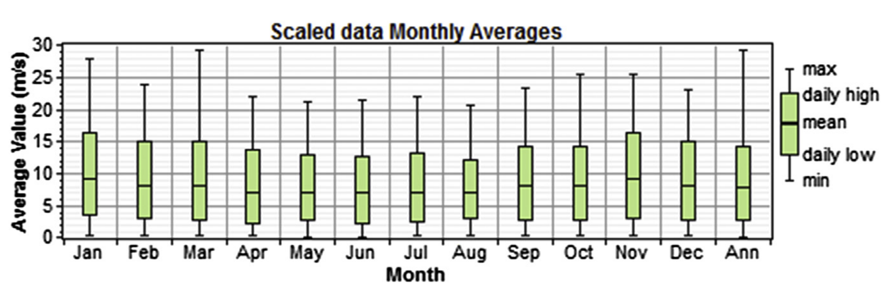

Fig. 8. Wind energy resources at Isle of Eigg.

Double click on a system below for optimization results.

Pri. Load 1 (kWh/d)		PV (kW)	KW6	Hydro (kW)	DSL (kW)	S4KS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	DSL (hrs)
856.000		53.4	4	119	80	96	45	$ 0	62,568	$ 881,829	0.200	0.89	17,895	1,045
1000.000		53.4	4	119	80	96	55	$ 0	77,231	$ 1,088,484	0.212	0.83	28,007	1,544

Fig. 9. HOMER Simulation results for the existing system.

Table 3
Annual energy generation from different energy sources.

Source	kWh/year (for demand of 856 kWh/day)	kWh/year (for demand of 1000 kWh/day)
PV array	26,508	26,508
Wind turbines	103,956	103,956
Hydro turbines	233,847	233,847
Diesel generator	44,830	72,500
Excess electricity	77,615	46,049
Renewable fraction	0.89	0.83

considered, a real discount rate of 5% has been used. Each simulation will be looking for the best configuration for two different load cases of 856 kWh/day as assessed from the monthly load demand and a higher demand of 1000 kWh/day to analyse the effects of load growth on the system.

5. Simulation results

The results of the simulation exercise are presented for the original system and an alternative system. In the first case, the capital investment is excluded as the funding came from grants and the simulation is constrained to the existing system configuration. This captures the running cost as well as any fixed maintenance cost that are associated with the existing system operation. In the second case, the initial investment is included and the optimisation search space is relaxed to generate the most appropriate configuration for the given load and resource conditions. Two alternative demand conditions are considered: 856 kWh/day and 1000 kWh/day for both the cases.

5.1. Original system

The optimal system selected by HOMER for the given load and resource conditions is very similar to the one existing at the Isle of Eigg. The cost of electricity (COE) is calculated to be £0.2/kWh for 856 kWh/day demand and £0.212/kWh for 1000 kWh/day demand. The actual price paid by the islanders is £0.20/kWh [5] – which shows that the tariff has been designed to recover the operating costs.

The only difference in configuration is that just one 80 kW diesel generator is chosen and only 45 kW of inverters are selected. This is much lower than what is actually installed at the site. Although the site has two 80 kW diesel generators, they never run simultaneously – thus a spare capacity of 80 kW is used when the other generator is under routine maintenance or has broken down. Instead of installing two large generators, a better alternative could have been to install 4 or 5 20 kW generators as back-up capacity, which would have reduced the investment cost and ensured a higher utilisation rate of the generators.

Similarly, HOMER selects a lower inverter capacity because of two reasons: first, day-time loads are fed directly from the AC generation that is available on site, thereby avoiding the entire energy to pass through the batteries and inverters, thereby

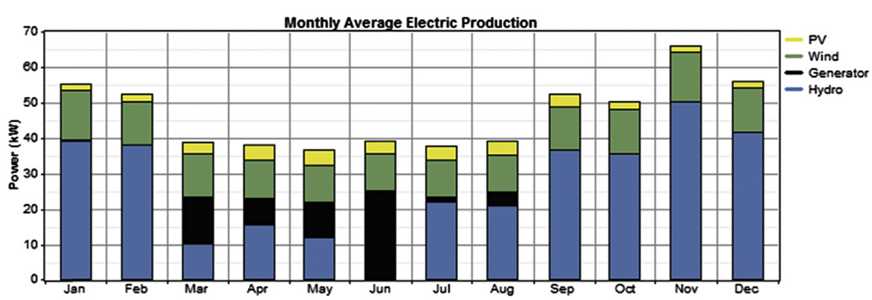

Fig. 10. Monthly average electricity production in Isle of Eigg system.

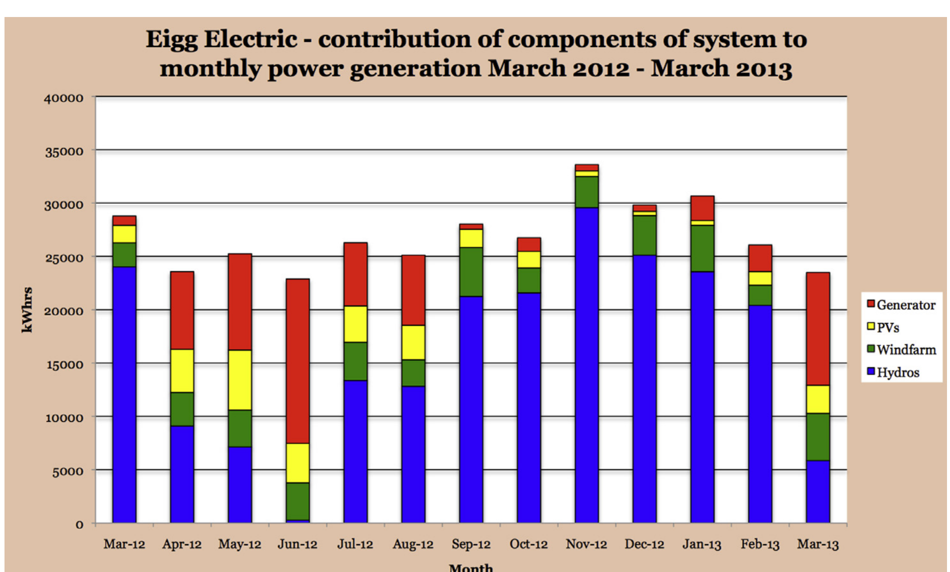

Fig. 11. Breakdown of energy production for each month [11].

Pri. Load 1 (kWh/d)	PV (kW)	KW6	Hydro (kW)	DSL (kW)	S4KS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	DSL (hrs)
856.000	53.4	4	119	80	48	45	$ 687,682	65,811	$ 1,615,219	0.367	0.89	21,095	1,478
1000.000	53.4	4	119	80	96	55	$ 741,365	77,128	$ 1,828,400	0.355	0.83	28,007	1,544

Fig. 12. Simulation results with initial cost incurred.

Pri. Load 1 (kWh/d)	PV (kW)	KW6	Hydro (kW)	DSL (kW)	S4KS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	DSL (hrs)
856.000	32.0	4	119	40	96	45	$ 694,078	59,865	$ 1,537,805	0.349	0.88	16,268	1,320
1000.000	32.0	8	119	80	96	65	$ 860,878	62,934	$ 1,747,871	0.340	0.92	15,973	919

Fig. 13. Optimal configurations chosen by HOMER for normal and higher demand.

reducing the losses. The on-site system has not been designed using this smart feature. Second, users on the site have a 5 kW cap (10 kW cap for businesses), whereas in HOMER it is impossible to apply such a constraint. The average load profile used in the simulation may have influenced the choice of lower inverter capacity (Fig. 9).

As can be seen HOMER has chosen the same configuration for both demand conditions, except that the converter size is 10 kW higher for the higher demand (1000 kWh/day) condition. It is logical that higher load requires more converters. Another interesting observation is the renewable energy fraction in two cases: for 856 kWh/day load, 89% of the energy supply comes from renewable sources but when the load increases to 1000 kWh/day, the diesel generator is used for an additional 500 h, using an additional 10,000 L of diesel and reducing the renewable share to 83%. This increases the cost of supply as well.

The simulation also suggests that the installed diesel generator capacity can meet the total demand at the site but this requires 223 kl of diesel and the cost of supply increases to £1/kWh, making it extremely costly. The operating cost increases 4.5 times compared to the optimal case and this option emerges at the worst alternative cost-wise. This justifies the renewable energy-based alternative as a viable option.

Table 3 provides a summary of energy generated from different sources under two load cases. The monthly production from each source is presented in Fig. 10. It can be noticed that diesel use is predominantly during the spring season when the hydropower is limited. Also note that the simulation retraces the actual monthly output shown in Fig. 11 quite well.

When simulation includes the initial cost of the system, the overall configuration changes depending on the system load. In the case of lower load, a smaller battery bank is chosen with only 48 batteries, but for the higher demand scenario HOMER selects the same configuration as before. The cost of electricity supply increases to £0.367/kWh and £0.355/kWh for 856 kWh/day and 1000 kWh/day respectively (see Fig. 12). The lower cost per kWh for the higher demand is obtained due to higher output. This shows that the full cost reflecting tariff is much higher than that being charged at the moment. However, given the project benefits from feed-in tariff for solar and wind power and compensation from Renewable Obligation Certificates (ROCs) for hydro power, we estimate that the project receives about £0.14/kWh as support on average. This is based on a feed-in tariff of £0.182/kWh for solar power, £0.264/kWh for wind power and a ROC price of £0.10/kWh for hydropower.[2] With this level of support and consumer tariff, the project almost recovers its full cost and maintains a good financial health.

5.2. Alternative system configuration

When a wider search space is given to HOMER, a slightly different configuration turns out to be more effective than the previous simulations. Initial costs are included in these simulations to reflect a real situation where the available amount of money plays an important role in choosing the configuration. Again to account for possible rise in demand simulation was run with two sensitivities of the load 856 kWh/day as current calculated average daily use and higher 1000 kWh/day. Fig. 13 presents the optimal solution for two demand conditions.

In both cases HOMER considers 32 kW of PV as adequate amount (53 kW in the existing system) and 96 batteries, the rest of the configuration differs. In case of 856 kWh/day demand the amount of wind turbines is the same as in current system but a diesel engine of 40 kW is suggested as the optimal size. It means that the current electricity demand can be satisfied with a smaller system – or in other words, the existing configuration is slightly oversized. For the 1000 kWhy/day scenario, 80 kW diesel generator is optimal. Also 8 wind turbines are suggested. This increases the initial costs but also increases renewable fraction to 92%, as less diesel fuel is burnt to power the system. A combination of higher renewable fraction in the system and the higher demand results in lower COE than in previous scenario and brings it down to £0.349/kWh and £0.34/kWh.

An important aspect to look at is excess of electricity produced. There is no such data available for existing scheme from the Eigg Electric Company but HOMER simulation suggests that for the original system the estimated excess is 10.5% but this figure goes up to 21.6% in the alternative system configuration. This means that there is a mismatch between supply and demand at certain times causing the system to dump extra electricity that can be productively used at no extra cost. It is noted that a significant part of excess electricity is produced in colder months from September to February. At present, electric heaters are operated in the communal houses in the island which operate only when excess electricity is produced. Many other ways of possible utilization of the excess electricity can be considered. During the period when excess renewable energy is available, consumers could be provided a signal to use more electricity either by reducing the price or by giving them extra energy quota. Such signals can be provided through their energy monitors. Excess electricity can also be used for charging of electric cars as there is a plan to buy a communal car. Similarly, it is also possible to consider demand management options to improve system utilisation. Further research is required to analyse such issues for the island system.

Our simulation with a larger search space shows that some solutions used in the island are not exactly the best choice that could have been made. For example, instead of up scaling the PV farm, it may have been more effective to add more wind turbines, given the wind energy potential of the site. Limited solar irradiation received

[2] As ROC prices vary from one year to another, the price prevailing in summer of 2014 has been used from http://www.epowerauctions.co.uk/trackrecord.htm.

by the site does not justify any additional investment in solar power.

6. Discussion and lessons for developing countries

The Isle of Eigg off-grid electrification system clearly shows that an off-grid system can support the electrical energy needs of a modern life style. The residents of the island are enjoying a reliable supply of electricity that meets their requirements effectively but more importantly, their carbon footprint has fallen considerably as about 90% of their electricity comes from renewable sources of energy. It is reported that the CO2 emission per household in the island is 20% lower than the rest of the UK [5]. The first lesson from this experience is that a suitably designed off-grid system can be an effective electrification option for any developing country. This experience confirms that reliable and modern life-style enabling supply can be ensured through an off-grid system and that such a system is not inferior to the supply obtained from the main grid. The islanders receive 24 h supply and have no complains about the supply. This demonstrates that an off-grid supply need not be a temporary or a pre-electrification option. This is an important message given that policy-makers and users are not always aware of successful examples and inaccurate or wrong impressions influence their decision-making.

While the island system provides a reliable electricity supply, it also placed a demand cap on the consumers. The appropriate level of service and benefits desired by the consumers that they can afford plays an important role in the system design. It is likely that domestic consumers of rural areas in developing countries will demand much less electricity and their needs can be met with a much lower level of cap. At the same time, commercial, agricultural and small-scale industrial activities could be envisaged to achieve a better capacity utilisation of the system and to generate income for the supplier and the local community. The second lesson from the study is that a tailored solution that adapts to the local needs works better.

Yet, the cost of supply remains a major challenge. Based on our simulations of the Isle of Eigg system we find that the residents are paying a tariff that is equal to the operating cost of ensuring the supply without taking capital investment costs. Even this level of tariff is much higher than the tariff for a comparable supply from the central grid elsewhere. This is still the case despite the high share of hydropower in the electricity supply mix in this island. Although the residents have reduced their expenses on diesel fuel and alternative energy supply options (such as batteries), there is no denial of the fact that even the operating cost recovery makes the tariff high and unless the users are able to pay such high tariffs, an off-grid system cannot become operationally viable. In this example, islanders have accepted the cost as the alternative they relied on earlier was costlier. They also have the ability to pay but this remains an issue in many developing countries, particularly in rural areas where income may be limited and villagers may not afford to pay high charges. Thus the third lesson is to design an effective tariff system to ensure the financial viability of an off-grid system, without which a sustainable supply cannot be ensured. Unless the supplier is able to recover costs and provide for future replacement of components, such projects are cannot be sustained in the long-run. The feed-in tariff, where available, can help reduce the burden to some extent and promote private investment in this area. However, implementing a feed-in tariff system for off-grid areas in developing countries with a limited number of electricity consumers and poor institutional arrangement remains a challenge.

A related issue is the funding of the investment for developing the system. The initial investment for the off-grid system in the island was £1.66 million (that turns out to investment above £44,000 per resident). Clearly, mobilising such an investment is not a mean task. For this island, the funding came from various sources with residents contributing about 6% of the cost. Unless such capital subsidy arrangements can be developed, poorer countries will find implementation of off-grid electrification projects very challenging. Thus the fourth lesson that Isle of Eigg offers is that even in a developed country context, capital subsidy could not be avoided for off-grid electrification and that the poor in developing countries cannot be expected to pay for their off-grid electricity supply systems. Sufficient grant fund has to be mobilised to create the electricity infrastructure in developing countries.

This study also confirms that in order to ensure a reliable, round-the-clock supply from an off-grid system, demand assessment and demand management remains very crucial. There may be some periods of excess generation while there are other periods when the supply will be constrained. An equitable and fair energy budget for all users and a smart energy monitoring system are essential to ensure effective user engagement in managing the supply-demand balance. The islanders have ensured success of their system by learning to share the limited resource using the signals provided through their meters. The fifth lesson therefore stresses the need for active user participation. The success of the system crucially depends on the active co-operation of the users who manage their demand effectively using the energy monitoring system. In a small system with limited diversity of demand, balancing supply and demand is always a crucial task and just relying on the supply-side management cannot ensure a reliable supply.

Sixth, our simulations also highlight the importance of system design and component selection for a cost effective outcome. As indicated earlier, the island system was over-designed to ensure high system reliability. In fact, the diesel generator capacity itself is much higher than the demand, although such a non-renewable option would lead to an excessive cost of supply (£1/kWh). It has been pointed out earlier that similar levels of reliability could have been achieved with 80 kW of diesel generator capacity (instead of 160 kW installed at present) but this would require using smaller generator sets that can be maintained and operated as required. Similarly, a better result would emerge if more wind turbines were installed instead of solar PV in this site. We have also indicated that direct feeding of AC load from AC sources could reduce the inverter and battery capacity requirements and can enhance the reliability of supply (simply because the entire system does not depend on batteries in this case). The technical choice has significant cost implications, particularly for the capital investment and a careful system design with innovative smart features can offer better value for money.

7. Conclusion

This paper provides a real example of a successful off-grid electrification system in a Scottish island and confirms that it is possible to supply electricity 24/7 from a hybrid off-grid system to support the electricity needs of a community leading modern lifestyles. It thus clears the misconception that off-grid electrification is just a temporary or an inferior solution for the developing world and shows that a properly designed off-grid system can be a viable alternative to grid extension in remote areas. With 90% of electricity generated from renewable electricity and the back-up system being used occasionally, the local grid has successfully reduced its carbon emission from electricity generation and can be a role model for many off-grid projects.

The paper shows how important it is to carefully estimate the available renewable resources to design the system so that energy can be harnessed in the most efficient way. Demand management also plays an important role which requires active participation of the users. An enthusiastic user group that appreciates the challenges and plays the game for a co-operative solution has helped the island in sustaining its off-grid solution.

Developing countries that are in the process of enhancing electricity access can learn from this successful experience. Most communities to be electrified in these countries will have a much lower electricity demand than in this island as users would often look for basic lighting, mobile charging and some sort of micro-enterprising. This radically minimizes the cost of the micro-grid needed to fulfil these needs. In cases where continuous power is necessary some sort of backup power is needed, usually a diesel generator will serve that function. With careful initial planning, upsizing of the grid is totally possible in case of future development. Fulfilling higher demand also brings a lower cost per unit of electricity what can be crucial for poor developing communities.

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